

# Some comments on embedding inflation in the AdS/CFT correspondence

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## Abstract

The anti-de Sitter space/conformal field theory correspondence (AdS/CFT) can potentially provide a complete formulation of string theory on a landscape of stable and metastable vacua that naturally give rise to eternal inflation. As a model for this process, we consider bubble solutions with de Sitter interiors, obtained by patching together dS and Schwarzschild-AdS solutions along a bubble wall. For an interesting subclass of these solutions the bubble wall reaches spacelike infinity in the black hole interior. Including the effects of perturbations leads to a null singularity emanating from this point. Such solutions are interpreted as states in a single CFT, and are shown to be compatible with holographic entropy bounds. The construction suggests de Sitter entropy be interpreted as the total number of degrees of freedom in effective field theory, with a novel adaptive stepsize cutoff.

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## I. INTRODUCTION

In recent years convincing evidence has accumulated that string theory has a vast landscape of consistent vacuum states, along with numerous long-lived metastable states that may well be relevant for realistic cosmology[1]. It is important to develop tools in string theory that are capable of describing transitions between such states. Currently the AdS/CFT formulation of string theory [2] is the most promising nonperturbative formulation of string theory. It is the purpose of the present paper to study how this landscape might be embedded in this framework, building on the earlier work of [3, 4].

We begin by reviewing classical bubble solutions in asymptotically AdS space, following the original work of [5]. For many of the most interesting solutions, the bubble wall appears to reach AdS infinity in finite time. We show this situation is unstable to perturbations, and that instead a null singularity emanates from this point. We discuss how this is to be interpreted in terms of the CFT, and propose a new interpretation of de Sitter entropy compatible with this picture.

## II. REVIEW OF CLASSICAL BUBBLE SOLUTIONS

In order to obtain solutions describing bubbles with inflating interiors inside asymptotically anti-de Sitter space, we follow the procedure of Blau, Guendelman and Guth [5]. The basic idea is to consider a spherically symmetric bubble in the thin-wall limit. The interior of the bubble is modeled by a piece of pure de Sitter space and the exterior by Schwarzschild-anti de Sitter space. This reduces the problem to specifying the radial position of the bubble as a function of time which reduces to the one-particle potential scattering problem described in [3]. In [3] the case of general dimension and charge was considered. Here we will specialize to the case of vanishing charge and asymptotically  $AdS_4$  spacetime. These solutions are similar to those considered in [5] and were studied extensively in [4]. The main features of all the solutions can be found in the following two examples in figure 1 and 2, that we will discuss in detail.

It is important to understand how these solutions change when subject to small perturbations. One issue is whether the spherical symmetric approximation is valid. This was considered some time ago in the context of the original work by Blau et al. [6, 7]. While

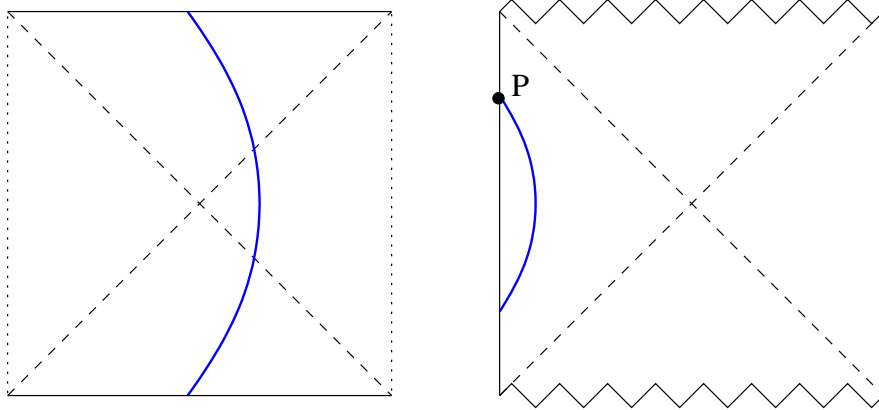


Figure 1: Penrose diagrams showing a time symmetric bubble trajectory. The left diagram refers to de Sitter space, the right diagram refers to Schwarzschild-anti de Sitter space. The bubble trajectory is shown in blue. The right segment of Schwarzschild-anti de Sitter corresponds to the exterior of the bubble. The left segment of de Sitter corresponds to the interior.

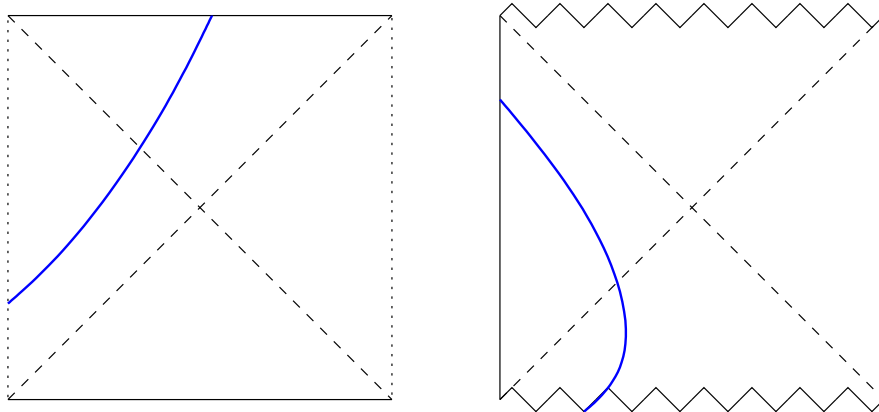


Figure 2: Penrose diagrams showing a time asymmetric bubble trajectory.

perturbations do indeed grow in the de Sitter interior, these do not qualitatively change the behavior of the solutions. Another issue peculiar to the situation with negative cosmological constant is what happens to the asymptotically anti-de Sitter boundaries that appear on the left. This is investigated in appendix A. For the time asymmetric case, figure 2, the conclusion is that a null singularity emerges from the point at which the bubble wall hits spacelike infinity. When one goes beyond leading order in perturbation theory, we believe this singularity should become spacelike, becoming null as it approaches the bubble wall. This is shown in figure 3.

Since these solutions are ultimately to be embedded in string theory, the de Sitter regions

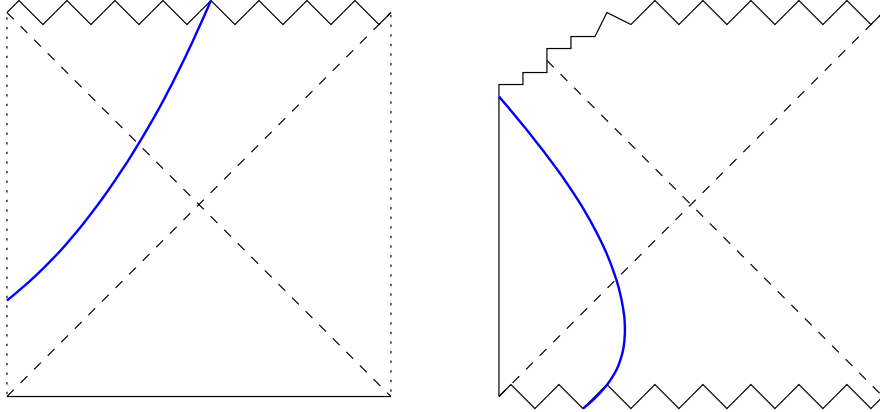


Figure 3: Time asymmetric perturbed bubble solution.

will be metastable. We will assume the anti-de Sitter vacuum under consideration is completely stable. There will therefore be tunneling between the two solutions. In particular, any timelike trajectory in the de Sitter interior will tunnel back to the vicinity of the anti de Sitter vacuum state, with a timescale exponentially smaller than the Poincare recurrence time of the de Sitter space. As shown in [8, 9] these regions undergo a crunch. We have schematically shown this in figure 3 as a future singularity in the de Sitter Penrose diagram.

In fact, the situation is more complicated than this, because while a given timelike curve will eventually enter a crunching region, the volume of a given set of compact spacelike slices will increase sufficiently fast that there is always remnant de Sitter space left at arbitrarily late time (see for example [10]). However for the purpose of predicting experiments measured by a local observer, a locally defined measure, implicit in figure 3, is most useful, rather than a volume weighted measure.

The same considerations apply to the time symmetric situation of figure 1. Once again, perturbations will generate a singularity emerging from the endpoint of the bubble wall, extending into the exterior Schwarzschild-anti de Sitter region. Of course, if one demands time symmetry, this will also extend outward from the starting point of the bubble wall. Likewise, on the interior, one must also take account of the fact that any timelike path will eventually tunnel to a crunch, so the asymptotic de Sitter future (and past) is effectively removed. This is shown in figure 4. Solutions of the type shown in figure 1 can only be obtained by a high degree of fine tuning. It seems unlikely such solutions would emerge from the underlying conformal field theory description for finite values of Planck's constant.

The version of the AdS/CFT correspondence advocated in [11] maps geometries with

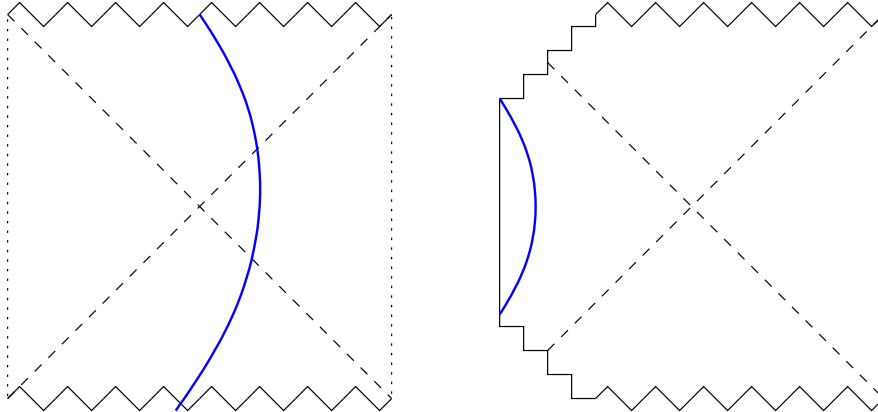


Figure 4: Time symmetric perturbed bubble solution.

a fixed boundary conditions at infinity (modulo conformal transformations) to conformal field theory on the boundary. We have seen that when perturbations are taken into account the bubble solutions have only a single asymptotically AdS region, therefore we expect a description in terms of a single conformal field theory. The simplest interpretation is in terms of pure states in the CFT [29]. That said, it is a subtle question how one constructs approximate local quantities behind the horizon for geometries such as figure 3. In the work of [12], where static black holes were considered, this was accomplished using analyticity, so that in general CFT correlators needed to be continued to complex values of space and time. For eternal Schwarzschild-AdS black holes, this can be reformulated in terms of the thermofield double formalism, and hence mixed states as in [4]. However unlike in [4], we no longer have another asymptotically AdS exterior region behind the horizon, so it is no longer possible to construct a precisely defined set of observables associated with this region. So there is no obvious inconsistency with a pure state description. We consider the implications of this picture and the quantum consistency of these solutions, once we have tackled the issue of interpreting de Sitter entropy in this framework.

### III. DE SITTER ENTROPY

Each of the bubble solutions considered above share the property that the expanding de Sitter region is behind a black hole event horizon from the viewpoint of the AdS boundary. These solutions are to be mapped into states in the boundary CFT, so we should associate them with particular black hole microstates. Moreover, as emphasized in [4], these states

will yield distinctive correlators which lead to the hope that there might be a practical way to select such states from a thermal ensemble. For large black holes in AdS (and many other examples in string theory) the Bekenstein-Hawking entropy  $S_{BH}$  is identified with the logarithm of the number of microstates. This leads to the conclusion that the number of de Sitter bubble states should be bounded by  $e^{S_{BH}}$ .

However it is not entirely clear how to interpret the Gibbons-Hawking entropy of de Sitter space [13]. Some earlier discussions of this in the context of AdS/CFT can be found in [14]. Another interesting attempt at interpreting de Sitter entropy in terms of effective field theory can be found in [15]. Suppose we imagine effective field theory in a de Sitter background with an ultraviolet energy cutoff  $\Lambda$  and an infrared length cutoff  $L$ . If we identify  $L$  with the horizon size of our present universe and the number of possible states in the effective field theory with the Gibbons-Hawking entropy, we obtain  $\Lambda = 100$  MeV. A more stringent bound is obtained if we restrict attention to those states with small gravitational back-reaction, demanding that the total energy not be inside its own Schwarzschild radius. Again taking  $L$  to be the horizon size today, we obtain  $\Lambda = 10^{-2.5}$  eV. Clearly there does not seem to be a conventional effective field theory description that extends from horizon size scales down to scales probed in accelerator experiments.

In this work we advocate a variant on this idea that receives support from some numerical coincidences. It was assumed above that the ultraviolet cutoff is a simple uniform cutoff everywhere in spacetime. However we know, for example from [12, 16, 17], that there is a complex relation between a UV cutoff in the bulk and physics in the CFT on the boundary, and that this is in general state dependent. Since we don't have a straightforward way to identify the de Sitter bubble states in the CFT, we will make the optimistic assumption that the bulk state is encoded using perhaps the most efficient coding one could imagine, an adaptive stepsize with many points appearing near aggregations of matter/energy, and few points appearing away from such regions. The current entropy of the universe is dominated by cosmic microwave background photons with  $S_{CMB} \sim 10^{85}$  [30] and with Compton wavelengths of around  $\lambda = 1$ mm. Current experiments have tested effective field theory out to about  $\Lambda = 1$  TeV, so an estimate of an upper bound on the log of number of possible states in effective field theory would be

$$S_{tot,CMB} = (\lambda\Lambda)^3 S_{CMB} = 10^{130}.$$

Of course it might be something of an overestimate to require so many states associated with a single CMB photon. Taking into account correlations between different states would certainly lower the total number, but it is not clear how to estimate the magnitude of this effect. Suppose instead we estimate a lower bound by considering states associated with individual hydrogen atoms. There are approximately  $10^{80}$  atoms in our horizon volume, with a size of  $\lambda = 5 \times 10^{-11}\text{m}$ . Estimating the associated log of the number of states gives

$$S_{tot,atoms} = (\lambda\Lambda)^3 10^{80} = 10^{103}.$$

So we see these crude estimates on the number of possible states in an adaptive stepsize effective field theory brackets the Gibbons-Hawking entropy

$$S_{tot,atoms} < S_{GH} = 10^{122} < S_{tot,CMB}$$

Henceforth we will adopt the view that the Gibbons-Hawking entropy counts the number of possible states in effective field theory, albeit one with a rather clever UV cutoff.

According to this picture, if we want to have a useful effective field theory description around a semiclassical de Sitter background, the total number of available states should saturate the Gibbons-Hawking entropy. This will be our criterion for deciding when a local observer would regard herself as living in a semiclassical de Sitter region. Most states in conformal field theory correspond to backgrounds without a geometric interpretation. Likewise one can expect many states where some observables correspond to a particular geometric background, but many other observables do not, causing an effective field theory description to break down. So this criterion leads to the conclusion that if the CFT states are to be identified with black hole microstates, one must respect the bound

$$S_{BH} > S_{GH} \tag{1}$$

in order that the interior of the bubble have an interpretation as a semiclassical spacetime.

Another logical possibility is that the bubble solutions require extra degrees of freedom, beyond those present in a single CFT, as advocated in [4]. In that picture, the CFT on the left boundary of Schwarzschild-AdS is regarded as being deformed. The correlations between those degrees of freedom and those in the CFT on the right induce a mixed state reduced density matrix, when the left boundary CFT is traced over. These ideas were most precisely stated for solutions such as figure 1, where the asymptotic AdS region is replaced

by a segment of de Sitter space for a finite period of time. It was argued in [4] that this corresponds to a non-local perturbation of the left CFT. If one goes beyond the thin-wall limit, we expect similar physics to emerge from a suitable local irrelevant perturbation of the left CFT. In fact one could dispense entirely with the right boundary in this picture, and study the CFT deformation on the left corresponding to the bubble. This is closely related to the proposal of [18, 19, 20, 21] where an irrelevant perturbation of  $\mathcal{N} = 4$   $SU(N)$  Yang-Mills was conjectured to be dual to gravity in asymptotically flat space. Related ideas where the asymptotically AdS structure is changed via CFT perturbations also appears in [22, 23][31]. If this picture was consistent, it would offer a very different interpretation of de Sitter entropy, since there are an unlimited number of UV degrees of freedom in the left CFT that might be associated with bubble geometries, and hence no apparent bound by the black hole entropy. However there is no strong evidence that effective field theories deformed by these irrelevant perturbations really have continuum limits, suggesting the UV completions are ill-defined. This is good news for AdS/CFT as a nonperturbative description of string theory, since in order for it to be complete and self-consistent, one should not need to add additional degrees of freedom every time a quantum fluctuation creates a region of spacetime causally disconnected from the boundary.

#### *Implications for de Sitter bubbles*

Time symmetric bubbles (and solutions related by diffeomorphism) always respect the bound  $S_{GH} > S_{BH}$ , [4]. So we conclude that when the microscopic description of the solution is taken into account via the CFT, there are not enough available states to represent a full semiclassical spacetime inside the bubble. These solutions are therefore spurious once quantum effects are taken into account.

All solutions where the bubble wall stays in a single region of the Schwarzschild-anti de Sitter Penrose diagram fall into this class. Quantum tunneling solutions involving smooth initial data, as in [24], involve transitions between classical solutions of this type. We see therefore that the rate of tunneling up the potential vanishes in the AdS/CFT framework for quantum gravity. Another argument for the vanishing of this tunneling rate is given in appendix B.

On the other hand, time asymmetric solutions of the type shown in figure 3 exist where



the bound (1) is satisfied. These solutions pass the quantum consistency condition described above. In classical relativity it is not clear whether a state emerging from singular initial data is physically meaningful. In a complete formulation of quantum gravity such as AdS/CFT this objection must be revisited. In the case at hand we have a set of solutions that involve an initial singularity, however all the indications are that these correspond to well-defined states in the CFT. We regard these black hole microstates as the most promising way to obtain a description of inflation embedded in the AdS/CFT correspondence.

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### Appendix A: GENERIC PERTURBATIONS OF BUBBLE SOLUTIONS

Various solutions in this paper, have the property that an asymptotically AdS region meets another asymptotic region at some instance in time. Here we will show that such behavior is highly non-generic, and that once perturbations are taken into account, the would-be Cauchy horizon that emanates from this intersection point instead becomes a null singularity, once leading order effects are considered. It is expected this null singularity will become spacelike, once higher order effects are incorporated.

To see this, we consider the following analog problem that is believed to capture the essential physics. We take neutral matter in the form of a scalar field of mass  $m_s$  and set up the equations of motion in a spherically symmetric ansatz. The solutions should be qualitatively the same as matter with nontrivial angular momentum. It is helpful to set up the Einstein equations with the variables similar to those used in [25]

$$ds^2 = g_{ab}dx^a dx^b + r(x^a)^2 d\Omega^2$$

with the radius and time directions denoted by  $x^a$ ,  $a = 1, 2$ . It is helpful to define

$$f \equiv g^{ab}r_{,a}r_{,b} \equiv 1 - 2m(x^a)/r$$

$$\kappa \equiv -m(x^a)/r^2$$

$$T = T_a^a, \quad P = T_\theta^\theta = T_\phi^\phi$$

so that the Einstein equations become

$$\begin{aligned} r_{;ab} + \kappa g_{ab} &= -4\pi r(T_{ab} - g_{ab}T) \\ m_{,a} &= 4\pi r^2(T_a^b - \delta_a^b T)r_{,b}. \end{aligned}$$

Here the stress energy tensor is defined to include matter contributions as well as the contribution from the cosmological constant. Conservation of the stress energy tensor yields the equation

$$(r^2 T^{ab})_{;b} = (r^2)^{,a} P.$$

At this point we specialize to compute the behavior of the metric near the boundary of AdS, near point P where the bubble wall reaches the cylinder at spacelike infinity as shown in figure 1. Outside the future cone of P and exterior to the bubble, the mass function takes the form

$$m(r) = m_0 + \Lambda r^3/6$$

with the cosmological constant related to the AdS radius of curvature  $R$  by  $\Lambda = -3/R^2$ . The main point is that if the geometry is no longer asymptotically AdS to the past of some point, generic matter perturbations will induce both the normalizable and non-normalizable modes with respect to asymptotically AdS geometry. Both of these perturbations become normalizable in the geometry to the past of point P. The stress energy of the “non-normalizable” modes diverges as  $r \rightarrow \infty$  for  $\Delta > 3$

$$\begin{aligned} T_{tt} &\sim r^{2(\Delta-3)} \\ T_{rr} &\sim r^{2(\Delta-4)} \\ T_{\theta\theta} &\sim T_{\phi\phi} \sim r^{2(\Delta-3)}. \end{aligned}$$

Here the conformal dimension  $\Delta$  is related to the mass of the scalar field  $m_s$  by  $\Delta = 3/2 + \sqrt{9/4 + m_s^2 R^2}$ . For sufficiently large  $\Delta$  this will dominate over the cosmological constant contribution as  $r \rightarrow \infty$ . In this limit, one obtains the equation

$$\square m = -16\pi^2 r^3 T_{ab} T^{ab}. \tag{A1}$$

Our strategy will be similar to that of [25, 26], namely we will treat the back-reaction of the stress energy on the geometry at leading order in perturbation theory around an

asymptotically AdS geometry. This will lead to a curvature singularity as one approaches the future light-cone of the point P.

To proceed, we solve (A1) using Kruskal coordinates. Outside the future light-cone of point P, we can use the pure AdS metric near infinity

$$ds^2 = (1 - \Lambda r^2/3)dudv + r^2 d\Omega^2$$

where the new coordinates are related to the old coordinates by

$$u = -t + r^* \quad , \quad v = t + r^* \\ r^* = \sqrt{\frac{3}{|\Lambda|}} \arctan \left( \sqrt{\frac{|\Lambda|}{3}} r \right) .$$

In these coordinates (A1) takes a simple form

$$\frac{\partial^2 m}{\partial u \partial v} \sim -cr^{4\Delta-9}$$

where  $c$  is a constant dependent on the amplitude of the matter perturbation. The solution for  $m$  is divergent as one approaches the future light-cone of the point P ( $v = \frac{\pi}{2} \sqrt{\frac{|\Lambda|}{3}}$ )

$$m \sim \frac{1}{(v - \frac{\pi}{2} \sqrt{\frac{|\Lambda|}{3}})^{4\Delta-7}} .$$

This provides strong evidence for at least a null singularity extending out on the future light-cone of the point P. Eventually higher order terms will come to dominate and the perturbative analysis breaks down, as is expected in [25, 26]. It is expected that the null singularity becomes a true spacelike singularity in the full non-linear analysis.

## Appendix B: DETAILED BALANCE

The implications of detailed balance for quantum tunneling from flat space to de Sitter space has been previously studied in [27]. Let us reconsider that argument in the present context. Detailed balance implies the transition probabilities between any two states  $i, j$  are related by

$$\Gamma_{ij} p_i = \Gamma_{ji} p_j$$

where  $\Gamma_{ij}$  is the transition rate from state  $i$  to state  $j$  and  $p_i$  is the equilibrium probability of state  $i$ . Consider  $AdS_4$  in thermal equilibrium, with large radius of curvature  $R$  and temperature  $T$ , in the regime where Schwarzschild-anti-de Sitter space dominates the canonical

ensemble. Let us suppose there exist some states in this ensemble corresponding to a small region of the Schwarzschild-AdS spacetime tunneling off into a de Sitter bubble. We assume the initial size of the bubble is the smallest length scale in the problem. Applying detailed balance to a transition between two such states, we obtain

$$\Gamma_{up} = \Gamma_{CDL} e^{S_{GH} - S_{BH}} \sim e^{-aR^2 T^2} \quad (\text{B1})$$

where  $\Gamma_{CDL}$  is the Coleman-De Luccia tunneling rate,  $\Gamma_{up}$  is the rate of tunneling up the potential,  $S_{BH}$  is the entropy of the Schwarzschild-AdS spacetime and  $S_{GH}$  is the Gibbons-Hawking entropy of a single de Sitter bubble, and  $a$  is a coefficient independent of  $T$  [28]. In this limit  $S_{BH} \sim aR^2 T^2$  which we take to be much larger than  $S_{GH}$ . We expect  $\Gamma_{CDL}$  to be independent of  $R$  and  $T$  in this limit, since it should be dominated by local physics.

The temperature dependence of the upward tunneling rate can be estimated as follows. Suppose an excited state with energy  $M$  is assembled, capable of tunneling to the de Sitter bubble. The probability of such a state will be  $e^{-M/T - S_{BH}}$ . The rate of upward transitions will then be

$$\Gamma_{up} = \Gamma_{tunnel} e^{-M/T} \quad (\text{B2})$$

where  $\Gamma_{tunnel}$  and  $M$  should be independent of  $T$  and  $R$  by locality. However the two rates (B1) and (B2) have different temperature dependencies, so cannot match. This implies the rate of quantum tunneling  $\Gamma_{tunnel}$  must vanish. This provides an argument, independent to that given in section III, that quantum tunneling up the potential, as envisioned in [24], does not happen. Nevertheless we do expect transitions between states of the type shown in figure 3 and Schwarzschild-AdS geometries, and these should be governed by the rate (B1).

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internal states of these objects, so their contribution will remain subdominant.

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